AD

TECHNICAL REPORT ARCCB-TR-01008

RAREFACTION WAVE GUN PROPULSION

E. KATHE
R. DILLON
S. SOPOK
M. WITHERELL
S. DUNN
D. COATS

APRIL 2001

US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

20010427 001

DISCLAIMER

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The use of trade name(s) and/or manufacturer(s) does not constitute an official endorsement or approval.

DESTRUCTION NOTICE

For classified documents, follow the procedures in DoD 5200.22-M, Industrial Security Manual, Section II-19, or DoD 5200.1-R, Information Security Program Regulation, Chapter IX.

For unclassified, limited documents, destroy by any method that will prevent disclosure of contents or reconstruction of the document.

For unclassified, unlimited documents, destroy when the report is no longer needed. Do not return it to the originator.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 2001	Final

4. TITLE AND SUBTITLE

RAREFACTION WAVE GUN PROPULSION

5. FUNDING NUMBERS

AMCMS No. 6330.04.43A1.1

6. AUTHOR(S)

E. Kathe, R. Dillon, S. Sopok, M. Witherell,
S. Dunn*, and D. Coats*
*Software and Engineering Associates, Inc., Carson City, NV

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army ARDEC
Benet Laboratories, AMSTA-AR-CCB-O
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER

ARCCB-TR-01008

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

This work was presented at the Advanced Gun Propulsion Concepts Session of the joint meeting of the JANNAF Interagency Propulsion Committee, 13-17 November 2000, Monterey, CA, and at the Advanced Propulsion Technologies Session of the 22nd Army Science Conference, 11-13 December 2000. It received best in session recognition at both symposia.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

RArefaction waVE guN (RAVEN) propulsion constitutes a novel means to dramatically reduce the recoil momentum and heat imparted to future cannons during firing. The method may be considered a hybrid propulsion technology with features common to both closed-breech cannons and recoilless rifles. Reduction of recoil and gun heating would greatly facilitate large caliber gun integration within light future combat system (FCS) vehicles. Analysis of a RAVEN launcher comparable to the current 120-mm M256 firing an M829 kinetic energy round would impose 75% less recoil momentum and reduce barrel heating at the muzzle by 50%.

14. SUBJECT TERMS

Interior Ballistics, Recoilless Rifle, Nozzle, Gun Propulsion, Heat Transfer

15. NUMBER OF PAGES

18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ACKNOWLEDGMENTS

The authors would like to acknowledge the assistance and advice of Dr. Pat Vottis and Dr. John Zwieg, formerly of Benét; Dr. Bruce Burns, Terence Coffee, and Al Horst of the Army Research Laboratory; Mark Ford of Picatinny Arsenal; and the RAVEN test fixture design team at Benét including Bob Durocher, Mike Glennon, Ed Hyland, Bill Simard, and Rich Tortorici.

INTRODUCTION

The extreme lethality goals of the future combat system program require innovative armament solutions to circumvent traditional engineering barriers. RAVEN propulsion constitutes a novel armament technology inspired by the need to meet the requirements of the Army's Objective Force.

The Need for Recoil Mitigation

The firing of a large caliber gun imparts substantial momentum and kinetic energy to the projectile. By conservation of momentum, a reaction is applied to the gun that is equal and opposite to that of the projectile and any propellant gases ejected out of the gun. Ultimately this recoil momentum is imparted to the vehicle through the recoil cylinders, which may be considered a shock isolation system. Although the recoil system may provide some degree of isolation from the ballistic load, the shock severity imposed upon light fighting vehicles by large caliber guns can prove quite aggressive.

Ogorkiewicz (ref 1) has published a commonly cited recoil tolerance limit of fighting vehicles. The ratio of recoil momentum (often termed "impulse") to vehicle mass should not exceed 900 N·s/tonne. This ratio is a "rough empirical rule" that does not accurately reflect the effects of unusual design parameters.

A second metric commonly used to assess recoil shock severity is the ratio of average recoil force to vehicle weight, which may be related to the acceleration of gravity and expressed in gee's. (In this context, recoil force is the load exerted through the trunnion bearings by the gun mount as the recoil cylinders bring the cannon to rest.) Clearly this metric fails to incorporate many issues such as the height of the trunnions, which substantially alters the angular momentum imparted to the vehicle.

In simple terms, impulse affects the gross vehicular response, as the duration of recoil loads tends to be small relative to the fundamental period of vehicle motion upon its suspension. That is, impulse affects vehicle stability. Recoil force, on the other hand, directly drives the shock severity of recoil as it applies a D'Alembert load to items coupled to the hull. It also drives the structural requirements of the gun mount and hull interface, tending to increase mount weight with increased recoil force.

The impulse and trunnion loads for several known vehicles and two future fighting vehicles are shown in Figure 1. It is worth noting that advances in fighting vehicle design are increasing the recoil tolerability of modern fighting vehicles, as evidenced by the rather aggressive performance of the M8 Armored Gun System developed by United Defense (ref 2). This is in contrast to the widely held view that the recoil severity of the M551 was too aggressive (ref 3) with recoil metrics slightly less aggressive than those of the M8.

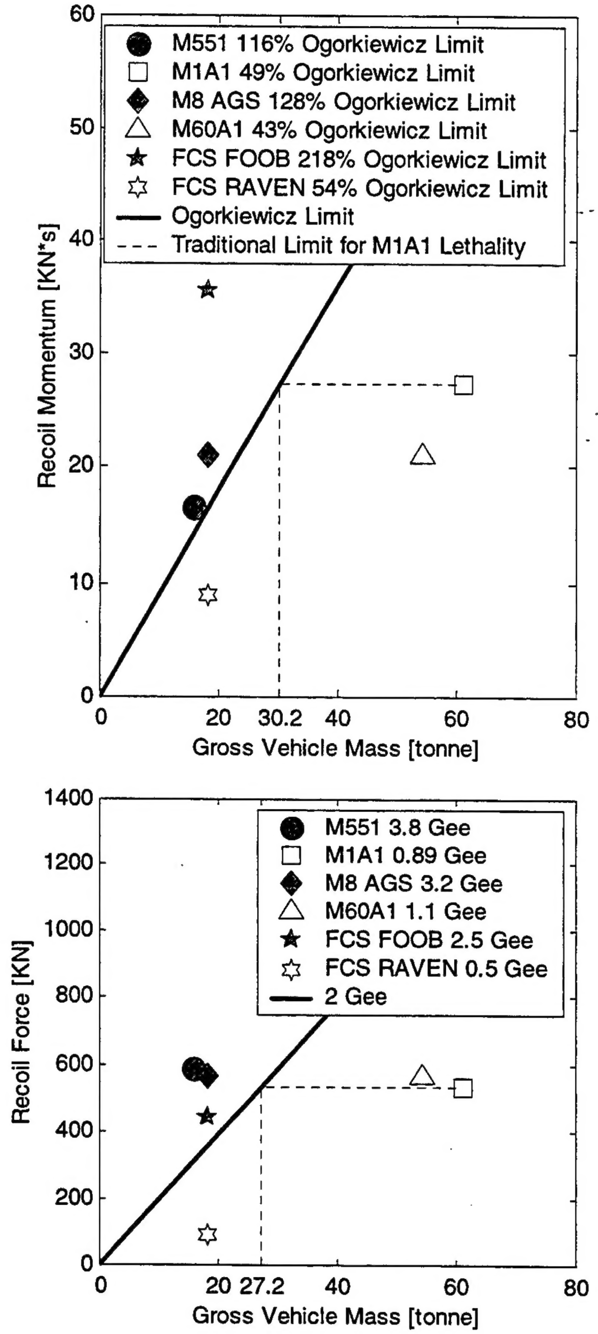


Figure 1. Plots of recoil shock severity metrics for fighting vehicles including two FCS vehicles.

Examination of intersections of lethality for a 120-mm tank gun, and traditional limits of light fighting vehicles to tolerate recoil depicted in Figure 1, support prior conclusions that the minimum vehicle mass of a future combat vehicle armed with a 120-mm gun would be 30 tons (27 tonne) (ref 3).

Two possible future combat system (FCS) armament configurations are shown. A fire-out-of-battery (FOOB) gun is included that may reduce recoil forces by a factor of three relative to that of a traditional recoil system (ref 4). A RAVEN launcher is also indicated assuming a 75% reduction in recoil momentum relative to that of a closed-breech gun. The RAVEN recoil forces and imparted recoil momentum are extremely low, providing growth potential of nearly 200% before exceeding the historical limits. A baseline traditional recoil gun is not shown since recoil forces of 1300 kN would not be feasible and would necessitate the use of an unusually long recoil stroke. Precedents do exist, however, for long recoil guns including the ARES, Inc. 75-mm MC-AAAC gun developed for the AAI Rapid Deployment Force Light Tank.

Further advances in active suspension technology and fire control systems that reduce reliance upon crew performance during recoil response are likely to continue this trend of increased recoil tolerability beyond that of the M8. However, the FCS program demands armament technologies with "unprecedented lethality" and "multi-functional capability" from future combat systems that are "up to 70% lighter" than current systems (ref 5). Achieving lightweight systems is a concern for two reasons. Decreasing recoiling mass or recoil stroke (to decrease vehicle weight and enable high-elevation firing for a multi-function gun) both increase the recoil force (ref 4). This counter-productive relationship between recoiling mass and recoil force is often not fully appreciated by those advocating lightweight cannon construction using composite materials.

For a point of reference, 36 kN·s of momentum imparted to an 18-tonne FCS vehicle through its center of mass by a FOOB gun would endow it with 2 m/s of velocity. The kinetic energy of the vehicle would be 36 kJ, sufficient to raise the vehicle about 20 cm off the ground. It should be understood the moment arm between the center of mass of the vehicle and gun trunnions would result in substantial rotational energy imparted to the vehicle as well.

The recoil demands placed upon the FCS are pushing the limits of modern armament technology's ability to evolve to meet the challenge without revolutionary innovation.

Basis of RAVEN Propulsion

RAVEN propulsion affords the armament engineer an altogether new means to efficiently propel a projectile forward at tank gun velocities with dramatically reduced momentum imparted to the gun (ref 6). The method may be considered a hybrid propulsion technology with features common to both closed-breech cannons and recoilless rifles. For the first stage of propulsion, the gun acts as a closed-breech gun. Later, it behaves as a recoilless rifle. One could also consider RAVEN to provide the action of a preemptive muzzle brake, but at the breech end of the gun.

RAVEN achieves this hybrid function by providing a delayed venting of propellant gases out of the rear of the chamber. This venting commences after peak ballistic pressure is attained, but well in advance of shot exit. Once the venting commences, a rarefaction wave[†] is released that

[†] Rarefaction is "the instantaneous, local reduction in density of a gas." In this case, it results from the venting of the high-pressure gases to atmospheric pressure through a nozzle. Like a sound wave, the speed of a rarefaction wave's travel is limited to the sonic velocity, in addition to the local velocity of the gases through which it propagates.

propagates toward the base of the moving projectile through the moving gas column at the sonic velocity. If the venting is delayed sufficiently, shot-exit will occur prior to any compromise in propulsion due to the venting—the projectile will never know the gun was vented. Venting that commences prior to this time will begin to compromise propulsion efficiency, while further decreasing recoil momentum. Venting that commences following this time will not have any effect on projectile propulsion, but will impair the reduction in recoil momentum.

Considering a traditional closed-breech gun as a single-stroke heat engine, the efficiency of a gun to achieve kinetic energy of the projectile is inherently limited by the finite expansion ratio of a cannon and the kinetic energy that is imparted to the propellant gases (the working fluid). The ballistic efficiency of typical guns is one-third, tending to be lower for high-velocity guns (ref 7).

RAVEN propulsion utilizes a substantial portion of the otherwise wasted propellant gas enthalpy to generate forward thrust that counteracts much of the momentum imparted to the gun prior to venting. The enthalpy applied to generating forward thrust would otherwise have become manifest as muzzle blast, recoil energy imparted to the gun during blow-down, and bore heating. Thus, the source of energy that RAVEN utilizes to generate forward thrust without compromising the propulsion of the projectile is no mystery.

120-MM M256/M829A2 CASE STUDY

For many, the M829A2 is considered the most lethal round in the inventory at this time. It, therefore, makes an excellent case study, as the lethality of an FCS should be equal to or greater than the current round.

Determination of Venting Time

The earliest time at which the chamber of a gun could be vented without compromise in the propulsion of the projectile is of interest. It may readily be computed from the output of a suitable interior ballistics code such as NOVA (ref 8). The sound speed may be estimated using ideal gas relationships, or more accurately using a compressible chemistry equilibrium and transport (CCET) code (ref 9). It may then be added to the local gas speed to determine the speed at which a rarefaction wave would travel. The rarefaction wave may be assumed at the muzzle contemporaneous with the base of the projectile at shot exit. The wave front may then be back propagated through time using Euler's method. The results for an ambient temperature firing of an M829A2 out of an M256 are shown in Figure 2.

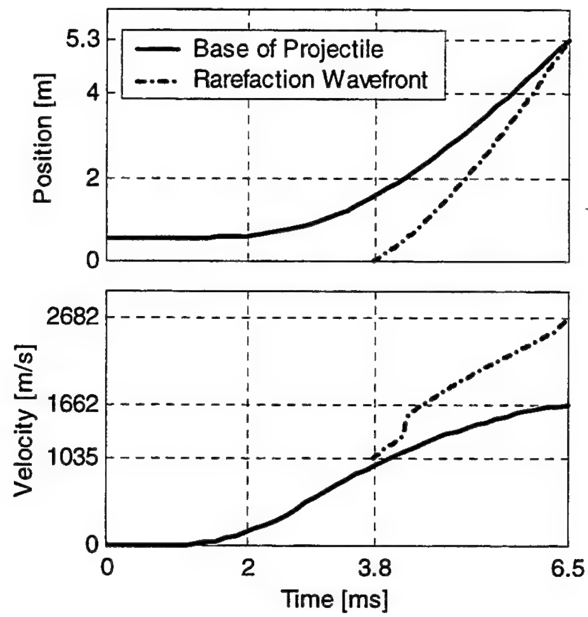


Figure 2. Plots of the position and velocity of both the base of the projectile and rarefaction wave front versus time.

Figure 2 results may be validated knowing the sonic velocity for propellant gas is estimated to be about 1000 m/s for most guns (ref 10). When added to the local gas velocity, which increases from zero at the breech to the muzzle velocity, the delay time may be approximated as gun length divided by the sum of sonic velocity and half the muzzle velocity. Using a length of 5.3-m and muzzle velocity of 1662 m/s per Figure 2, yields an estimated delay time of 2.9-ms. This estimate is very near to the 2.7-ms delay shown in Figure 2. Nevertheless, it is rather astonishing that theoretically, the back end of an M256 could be fully vented when the projectile has not yet traversed the first fourth of its travel down the gun without any compromise in its propulsion. Results of simulations of a high-zone firing of a 155-mm howitzer (XM297 zone 6), 25-mm chain gun (M242/M719), and the system of Figure 2 (M256/M829A2) indicate that venting may occur at 30%, 35%, and 24% of projectile travel for these systems, respectively (ref 11).

Estimation of Impulse Reduction

A crude lower-bound estimate of impulse reduction may be derived without resorting to additional computational fluid dynamics. If no expansion nozzle were used, but rather a simple, straight blow-back bore-sized nozzle were employed, the analysis would be simplified providing a better pedagogical perspective. No forward thrust would be generated, but no additional rearward momentum would be imparted once the vent were fully open. Clearly, an expansion nozzle could be designed to generate forward thrust, so this is truly a lower bound. The results

shown in Figure 3 indicate that a vent that opened instantaneously at 3.76-ms would prevent 58% of the momentum from being applied to the breech. A vent that began to open at 3.76-ms and was fully open at 4.21-ms would prevent more than 49% of the momentum.

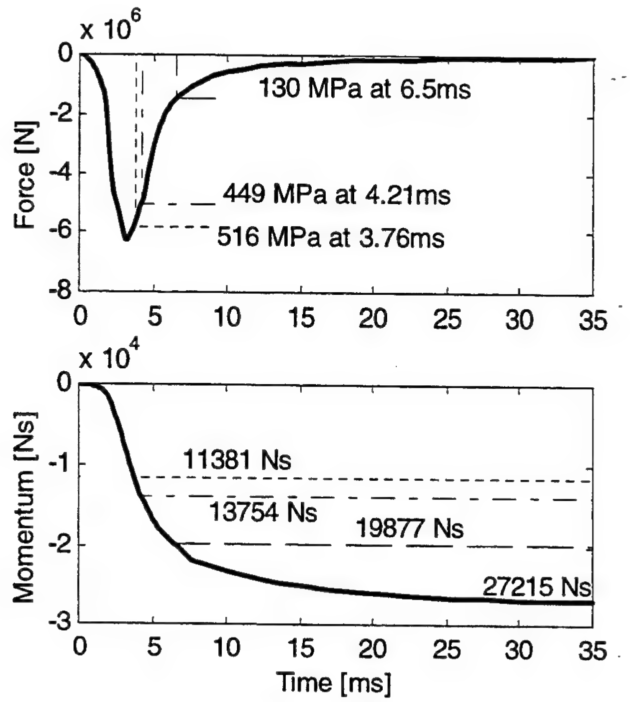


Figure 3. Plots of the ballistic forces applied to the cannon (rearward forces negative) and the accumulation of momentum.

For a more refined analysis of RAVEN propulsion, a new Navier-Stokes solver code was employed termed the gun tube boundary layer (GTBL) code. This code is being developed under a collaborative effort between Benét Laboratories and Software and Engineering Associates. The original intent of this code was to improve the boundary layer modeling for high-fidelity thermochemical erosion modeling of gun bore protective coatings.

The GTBL modeling incorporated a Mach boundary condition at the chamber vent, located at the breech face. The contraction ratio from the chamber to the throat of the vent was 10%. Behind the Mach boundary condition, a simple one-diameter nozzle was assumed with an exit diameter of nearly 1-m using the CCET code to account for real gas properties. Two cases were analyzed. The vent was assumed to open linearly in time over durations of 0.1-ms and 1-ms. One might picture this as a camera aperture opening at the breech. As the chamber diameter of the M256 is nearly 156-mm, the maximum diameter of "aperture" of the vent is 148-mm. Clearly, this is a simplification of any practical venting mechanism that may be employed. Nevertheless, the analysis should prove indicative of what may be achieved. The result for the 0.1-ms venting time is depicted in Figure 4.

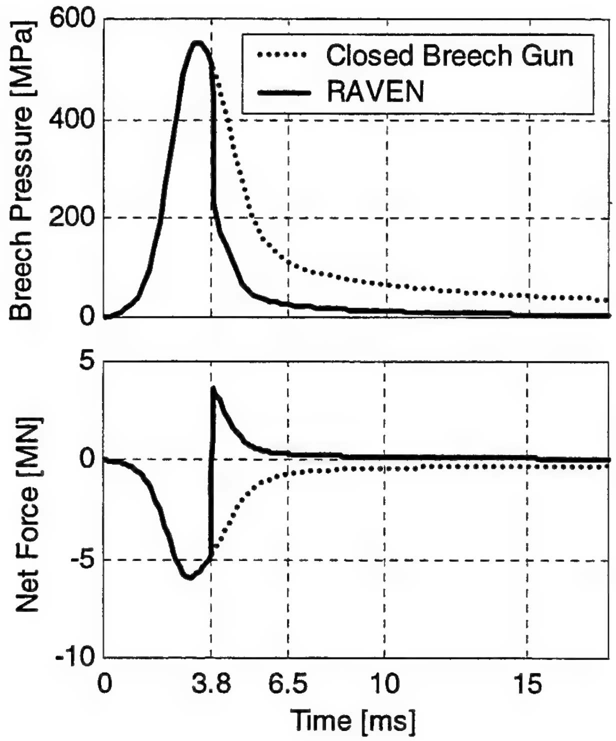


Figure 4. Plots of breech pressure and net force applied to a RAVEN launcher that includes developed thrust.

The reduction in momentum achieved using RAVEN with an expansion nozzle was in excess of 75%. Using the higher fidelity two-dimensional GTBL code demonstrated that the rarefaction wave would travel somewhat faster than the one-dimensional NOVA estimation due to the faster core flow down the center line of the bore. However, this will not appreciably alter the conclusions of the analysis.

To achieve this kind of recoil reduction using a muzzle brake would require a brake efficiency, β, of 2.78 using Corner's definition (ref 7). The most aggressive double-baffle howitzer brake used achieves a muzzle brake efficiency of 1.45.

Reduction in Bore Heating

An important consequence of RAVEN propulsion is the anticipated reduction in bore heating of the cannon. Heat transfer to the bore of a gun relates in a nearly linear fashion to gas density, gas velocity, duration of exposure, and the difference between gas and wall temperature (ref 12). A rarefaction wave by definition reduces the gas density, and it has the effect of sucking the propellant gas column backwards. This slows down the forward gas velocity, even reversing it for some portion of the gases. Since the gas is being vented out the gun prior to shot exit, the duration of blow-down is substantially reduced. Figure 5 depicts a computation of these effects on the relative bore heating of a RAVEN relative to the closed-breech gun.

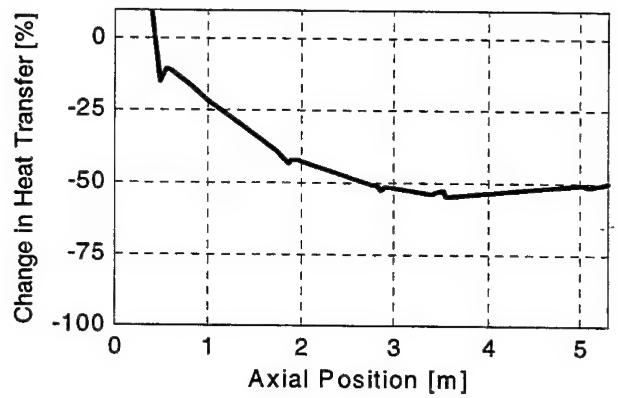


Figure 5. Plot of reduced bore heating of RAVEN relative to closed-breech gun.

It is worth noting that heat transfer actually increased in the gun chamber. For a closed-breech gun, there is little gas velocity to drive heat transfer. Overall heat input to the RAVEN cannon was cut by one-third.

VENTING MECHANICS

Despite the theoretical advantages of venting a large caliber gun after peak pressure but prior to shot exit, engineering a mechanism to achieve this objective is a daunting task. Of all the challenges inherent in RAVEN propulsion, this is the most likely to prevent ultimate weaponization if clever yet sound solutions cannot be engineered.

Two basic categories of vent mechanisms may be identified. Those employing some form of a blow-back mechanism (refs 13,14) and those employing some form of delayed rupture disk.

Inertial Breech

The most widely recognized form of an inertial breech is the Davis gun. Invented during the Great War, a Davis gun fires an ordnance projectile out the front and a dummy projectile out the rear (refs 13,15). The dummy projectile—composed of lead dust and Vaseline—may be considered to have provided inertial containment of the propellant gas pressure. Since the dummy projectile mass was comparable to that of the ordnance projectile, its kinetic energy was far too high to contemplate capturing for re-use. However, if the dummy projectile were to have a mass comparable to that of a recoiling cannon, the kinetic energy of recoil would prove manageable. Such a dummy projectile could better be described an inertial breech (ref 16).

Since RAVEN may be anticipated to reduce recoil momentum by 75%, the use of an inertial breech with one-forth the traditional recoiling mass of a gun would result in similar kinetic

energy of recoil. It is worth noting that the mass of a typical breech ring, whose function is obviated by the use of an inertial breech, would contribute toward a substantial portion of this mass.

An inertial breech may be employed to time the opening of an exhaust port behind the chamber in analogy with the means by which a two-stroke engine's piston uncovers its exhaust port. The timing of such a device should prove highly repeatable, as the ballistic loads imposed would greatly overshadow any unpredictable disturbances, such as those due to variation in friction. Variations in ballistic loads would affect both the inertial breech and projectile and thus would tend to self-compensate. The timing would be controlled by the inertia of the breech, the pressure-time profile of the round, and the geometric setback distance between the rear obturation of the inertial breech and the commencement of the exhaust port.

Figure 3 reveals that an inertial breech of 300 kg would be endowed with over 11,381 Ns of momentum at the point venting would commence. This would result in a velocity greater than 38 m/s. Using a simple annular geometry for the exhaust port, the venting area opened up by the recoiling inertial breech may be considered to have fully opened the vent when it has axially uncovered the port by a distance approximately equal to one-half the throat radius, or 37-mm for the RAVEN analyzed. This should take nearly 1-ms. Thus, employing the ballistic energy to drive an inertial breech may be seen to provide the required actuation energy to open a chamber vent with appropriate swiftness.

This actuation energy comes at a price; a slight decrease in muzzle velocity will occur for much the same reason that test engineers experience muzzle velocity reductions when live fire tests of new ammunition mature from a heavy Mann barrel to an objective cannon. The increased kinetic energy of recoil is removed from the propellant gases that are intended to drive the projectile. Muzzle velocity reductions of a few percent (3% for the case at hand) may be anticipated due to this effect (ref 17). This is wholly unrelated to the venting of a RAVEN launcher; it relates totally to the actuation energy required for the venting mechanism.

Figure 6 depicts an image of an inertial breech assembly engineered for validation testing of a 120-mm RAVEN launcher (ref 18). A modified XM291 120-mm gun barrel will screw into the breech ring shown to the right. (The breech assembly swings closed to meet proving ground safety requirements for the demonstrator.) A specially modified M829 stub case will be designed to shear, allowing the propellant gas pressure to punch out a 125-mm disk that will cover the front face of the inertial breech as it recoils. Once it recoils approximately 30-mm, the chamber gases will be vented to an annulus surrounding the front face of the inertial breech. The gases will then be reintroduced to an inner conduit within the inertial breech before being thrust out the expansion nozzle. This configuration will apply forward thrust directly to the recoiling breech, thus directly reducing its kinetic energy.

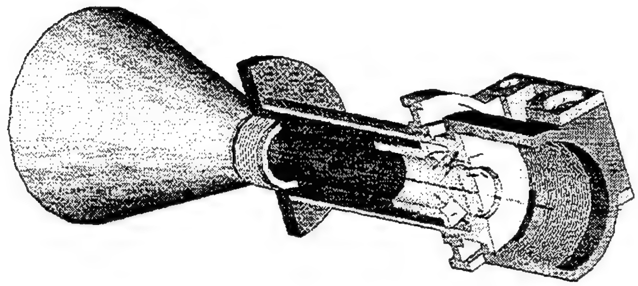


Figure 6. Image of an inertial breech assembly
for a 120-mm RAVEN validation launcher.

A throat diameter of 125-mm was chosen because it achieves a balance of ballistic loads applied to the cannon prior to venting. During the closed-breech period, axial tension loads continue to be applied to the cannon between the chambrage cone and stationary breech annulus. Because of the pressure gradient within the chamber, balance would not be achieved with a 120-mm throat. Achieving balance is not critical to the design of a RAVEN; however, a recoilless cannon barrel should prove far more accurate than a conventional cannon that is subject to traditional gun whip.

Wear and erosion of an inertial breech venting mechanism will prove a principal challenge to circumvent. However, the inertial breech was chosen for proof-of-principle demonstration due to its amenability to analysis and simple, yet reliable means of vent timing.

Detonated Rupture Disks

The Germans, in their development of recoilless artillery, first employed rupture disks (ref 10). The disks contained chamber pressure up to a pressure substantially less than peak pressure (about 10 MPa). This aided the ignition process for the propellant bed.

Such disks cannot be applied to RAVEN propulsion, as the venting must be delayed past peak pressure. However, a disk that was engineered to withstand peak pressure without rupturing, but that could be actively caused to fail at a predetermined time could be employed. Although mechanisms other than detonation may be envisioned, detonation is the most easily understood mechanism.

Since a detonated rupture disk would need to be replaced with each shot, and since its structure (mass) would have to be substantial to withstand the peak ballistic pressures, this approach places the burden of venting on the ammunition. However, the lightening of the gun system enabled by RAVEN (composite cannons make sense for RAVEN) would have a substantial favorable impact on the armament system mass.

BACK BLAST

An inescapable consequence of RAVEN propulsion is back blast. Concern regarding the safety of nearby infantry and noncombatants is warranted. No specific analysis of RAVEN back blast has yet been conducted; yet some comparisons may be drawn to the historical use of recoilless rifles in the past. Such comparisons must be understood to merely provide perspective in the absence of sound analysis and experimental validation.

It is important to realize that the back blast is directed away from the vehicle. This is in sharp contrast to muzzle brake blast, which directs shock waves directly at the vehicle.

The GTBL analysis of a venting that opened over a 1-ms duration, as might be anticipated from an inertial breech vent, concludes that the total rearward mass outflow will be 4.85 kg of propellant gas. This constitutes about one-half of the propellant mass used in the round. Experimental results firing the M27 105-mm rifle may prove indicative of the danger zone anticipated for a 120-mm RAVEN. Approximately 90% of the 3.6 kg of propellant used by the M27 during the tests was ejected out the back. (The impetus of the recoilless rifle propellant is only about 12% less than for RAVEN.) Due to the nature of the gas expansion from a point source, it may be anticipated that the increased distance of the danger zone will rise as a fractional power of the propellant mass, so assuming a 50% increase in the danger zone should more than accommodate the effect of the increased RAVEN propellant gas mass ejected rearward relative to that of the M27.

The danger zone for the M27 is considered to extend rearward about 25-m along the gun axis. At its widest extent, the danger area reaches about 4.5-m either side of the axis. The back jet is extremely dangerous within about 10 degrees either side of the gun axis up to a distance of about 9-m. It is considered lethal within 6-m (ref 19).

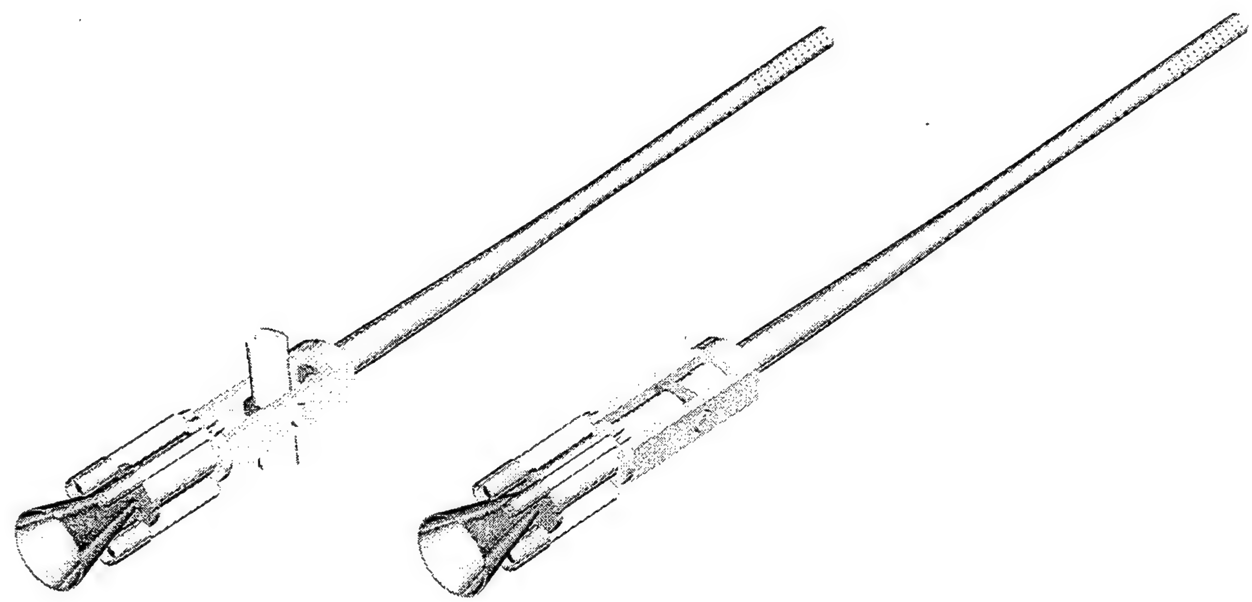
Using the M27 as a benchmark, the danger zone of a 120-mm RAVEN may extend 37-m rearward with an extremely dangerous zone extending 14-m rearward and a lethal zone within 9-m from the gun.

It is worthy to note that historically, "The most important single injuring factor is the missile effect of unburned propellant expelled at high velocity from the breech of the rifle, and that it is this factor that determines the maximum extent of the danger areas." Further, "Flame (flash) present in back blast presents an extremely minor hazard . . ." (ref 19).

Due to the delayed nature of RAVEN venting, the web thickness of any remaining propellant is extremely small. Independent analysis of an M256/M829A1 RAVEN indicated a total of 0.036 kg of propellant grains would be expelled with 0.06-mm of remaining web thickness at the commencement of venting (ref 17). This will tend to dramatically decrease the back blast danger zone for RAVEN.

AN OBJECTIVE RAVEN LAUNCHER

An excellent solution to the loading of a RAVEN is the use of a rotating or swing chamber gun configuration. Pioneered by Gene Stoner of ARES, Inc., such a gun facilitates integration with an autoloader by reducing the degrees-of-freedom required to load the gun at any elevation. An image of such a gun is depicted in Figure 7, with the swing chamber rotated open (ref 20). This gun autoloader interface has been the subject of development at Benet Laboratories and Picatinny Arsenal for over two years for a traditional closed-breech gun (ref 21).



(a) (b)

Figure 7. Image of 105-mm bore diameter inertial breech RAVEN with (a) open and (b) closed swing chamber.

It is worthy to note that such a gun will incorporate double recoil. The primary recoiling mass will consist of the inertial breech. The secondary recoiling mass will include the cannon barrel. Using this recoil approach, very high recoil loads may be applied by the primary recoil cylinders (shown in Figure 7) to bring the inertial breech to rest with respect to the cannon. Very low recoil loads may then be transferred to the vehicle through the secondary recoil cylinders.

RECOILLESS OPERATION

Achieving full recoilless operation without any degradation in projectile propulsion may prove beyond the reach of RAVEN technology. However, achieving full recoillessness will be possible by venting early, and allowing the rarefaction wave front to reach the base of the projectile.

The wave front is not manifest as an abrupt discontinuity in pressure; rather it is manifest as a gradual reduction in pressure. Specifically, the wave front appears as a discontinuity in the slope of the axial pressure distribution or pressure gradient. Therefore, the loss in ballistic efficiency for a slightly pre-released rarefaction wave will be small.

For most rounds, excepting long-rod kinetic energy penetrators, modest muzzle velocity losses might be more than compensated by the reduction in recoil momentum. Under certain circumstances, additional chamber volume may enable the muzzle velocity to remain at acceptable levels despite any losses in ballistic efficiency.

CONCLUSIONS

Recoil mitigation is of paramount importance to the successful fielding of future fighting vehicles armed with large caliber guns for the Objective Force.

- RAVEN propulsion provides revolutionary performance in recoil mitigation.
- The physics of RAVEN propulsion is sound and reproducible by others.
- The engineering challenges required to weaponize RAVEN propulsion for a large caliber main armament are substantial.

REFERENCES

1. Ogorkiewicz, R.M., *Technology of Tanks: Volumes I and II*, Jane's Information Group, Surrey, UK, 1991.

2. Heron, B.G., personal communication, United Defense, San Jose, CA, 8 March 1999.

3. Milton, F., "Army After Next Presentation Advocating a Hybrid Missile and Medium-Caliber-Gun Future Combat System," 21st Army Science Conference, Norfolk, VA, 15-17 June 1998.

4. Kathe, E., "Recoil Considerations for Railguns," *IEEE Transactions on Magnetics*, January 2001.

5. Kern, Paul J., LTG, "Future Combat Systems," Defense Advanced Research Projects Agency (DARPA) 21st Systems and Technology Symposium, Dallas, TX, 6-8 September 2000.

6. Kathe, E., "Sonic Rarefaction Wave Recoilless Gun System," U.S. Patent Application Serial Number 09/631,142, 2 August 2000.

7. Corner, J., *Interior Ballistics of Guns*, Wiley, New York, 1950.

8. Gough, P., "The XNOVAKTC Code," U.S. Army BRL-CR-627, Paul Gough Associates, Portsmouth, NH, 1990.

9. Coats, D., Dunn, S., and Sopok, S., "A New Chemical Equilibrium Code with Compressibility Effects," *Proceedings of the 33rd JANNAF Combustion Meeting*, Monterey, CA, October 1996.

10. Germershausen, R., and Melchior, E., "Internal Ballistics," *Handbook on Weaponry, First English Edition*, Rheinmetall GmbH, Düsseldorf, Germany, 1982.

11. Kathe, E., and Dillon, R., "Sonic Rarefaction Wave Low Recoil Gun," Paper AIAA-01-0743, January 2001.

12. Jones, R.N., Hitchcock, H.P., and Villegas, D.R., *Engineering Design Handbook: Ballistics Series: Interior Ballistics of Guns*, AMC Pamphlet AMCP 706-150, U.S. Army Materiel Command, Alexandria, VA, February 1965.

13. Hatcher, H.S., *Hatcher's Notebook*, Stackpole Company, Harrisburg, PA, 1962.

14. Chinn, G.M., COL, *The Machine Gun: Design Analysis of Automatic Firing Mechanisms and Related Components, Volume IV, Parts X and XI*, prepared for the Bureau of Ordnance, Department of the Navy, 1955.

15. Chinn, G.M., COL, *The Machine Gun: History, Evolution and Development of Manually Operated, Full Automatic, and Power Driven Aircraft Machine Guns, Volume I*, prepared for the Bureau of Ordnance, Department of the Navy, 1951.

16. Kathe, E., "Inertial Breech Gun System," U.S. Patent Application Serial Number 09/363,700, 16 July 1999.

17. Coffee, T., "RAVEN Simulations," presented at RAVEN Meeting, Picatinny Arsenal, NJ, 27 June 2000.

18. Glennon, M., Tortorici, R., Hyland, E., and Kathe, E., "RAVEN 120-mm Preliminary Design," U.S. Army Benét Laboratories, Watervliet, NY, June 2000.

19. Olcer, N.Y., and Levin, S., *Engineering Design Handbook: Recoilless Rifle Weapon Systems*, AMC Pamphlet AMCP 706-238, U.S. Army Materiel Command, Alexandria, VA, January 1976.

20. Glennon, M., Tortorici, R., Hyland, E., and Kathe, E., "RAVEN 105-mm Preliminary Design," U.S. Army Benét Laboratories, Watervliet, NY, October 2000.

21. Zangrando, R.A., "Swing Chamber Gun System," presented at Benét/FSAC Gun Systems Concept Brainstorm Session, Benét Laboratories, Watervliet, NY, 13 August 1998.

TECHNICAL REPORT INTERNAL DISTRIBUTION LIST

	NO. OF COPIES
TECHNICAL LIBRARY ATTN: AMSTA-AR-CCB-O	5
TECHNICAL PUBLICATIONS & EDITING SECTION ATTN: AMSTA-AR-CCB-O	3
OPERATIONS DIRECTORATE ATTN: SIOWV-ODP-P	1
DIRECTOR, PROCUREMENT & CONTRACTING DIRECTORATE ATTN: SIOWV-PP	1
DIRECTOR, PRODUCT ASSURANCE & TEST DIRECTORATE ATTN: SIOWV-QA	1

NOTE: PLEASE NOTIFY DIRECTOR, BENÉT LABORATORIES, ATTN: AMSTA-AR-CCB-O OF ADDRESS CHANGES.

TECHNICAL REPORT EXTERNAL DISTRIBUTION LIST

	NO. OF COPIES
DEFENSE TECHNICAL INFO CENTER ATTN: DTIC-OCA (ACQUISITIONS) 8725 JOHN J. KINGMAN ROAD STE 0944 FT. BELVOIR, VA 22060-6218	2
COMMANDER U.S. ARMY ARDEC	
ATTN: AMSTA-AR-WEE, BLDG. 3022	1
AMSTA-AR-AET-O, BLDG. 183	1
AMSTA-AR-FSA, BLDG. 61	1
AMSTA-AR-FSX	1
AMSTA-AR-FSA-M, BLDG. 61 SO	1
AMSTA-AR-WEL-TL, BLDG. 59	2
PICATINNY ARSENAL, NJ 07806-5000	
DIRECTOR U.S. ARMY RESEARCH LABORATORY ATTN: AMSRL-DD-T, BLDG. 305 ABERDEEN PROVING GROUND, MD 21005-5066	1
DIRECTOR U.S. ARMY RESEARCH LABORATORY ATTN: AMSRL-WM-MB (DR. B. BURNS) ABERDEEN PROVING GROUND, MD 21005-5066	1
COMMANDER U.S. ARMY RESEARCH OFFICE ATTN: TECHNICAL LIBRARIAN P.O. BOX 12211 4300 S. MIAMI BOULEVARD RESEARCH TRIANGLE PARK, NC 27709-2211	1

	NO. OF COPIES
COMMANDER ROCK ISLAND ARSENAL ATTN: SIORI-SEM-L ROCK ISLAND, IL 61299-5001	1
COMMANDER U.S. ARMY TANK-AUTMV R&D COMMAND ATTN: AMSTA-DDL (TECH LIBRARY) WARREN, MI 48397-5000	1
COMMANDER U.S. MILITARY ACADEMY ATTN: DEPT OF CIVIL & MECH ENGR WEST POINT, NY 10966-1792	1
U.S. ARMY AVIATION AND MISSILE COM REDSTONE SCIENTIFIC INFO CENTER ATTN: AMSAM-RD-OB-R (DOCUMENTS) REDSTONE ARSENAL, AL 35898-5000	2
COMMANDER U.S. ARMY FOREIGN SCI & TECH CENTER ATTN: DRXST-SD 220 7TH STREET, N.E. CHARLOTTESVILLE, VA 22901	1

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER, BENÉT LABORATORIES, CCAC, U.S. ARMY TANK-AUTOMOTIVE AND ARMAMENTS COMMAND, AMSTA-AR-CCB-O, WATERVLIET, NY 12189-4050 OF ADDRESS CHANGES.